Vegetable Response to Herbicides Applied to Low-Density Polyethylene Mulch Prior to Transplant

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Few herbicides are available for weed control in vegetable production systems using low-density polyethylene (LDPE) plastic mulch. With the elimination of methyl bromide for pest management and subsequent use of various alternative fumigants, the need for herbicides in vegetable production systems has increased. An experiment was conducted to evaluate tolerance of transplant summer squash and tomato to carfentrazone, flumioxazin, glyphosate, halosulfuron, or paraquat applied to the mulch prior to transplanting. After applying herbicides overtop of the mulch but prior to vegetable transplant, the mulch was either irrigated with 1.0 cm of water or not irrigated. Carfentrazone did not affect either crop regardless of irrigation. Irrigation readily removed glyphosate and paraquat from the mulch, as there was no adverse crop injury in these treatments. In the absence of irrigation, glyphosate and paraquat reduced squash diameter and tomato heights 18 to 34% at 3 wk after transplanting (WAT). Squash and tomato fruit numbers and fruit biomass (yield) were reduced 17 to 37%, and 25 to 33%, respectively. Halosulfuron reduced squash diameter and yield 71 to 74% and tomato heights and yields 16 to 37% when mulch was not irrigated prior to transplanting. After irrigating, halosulfuron had no affect on tomato, but reduced squash growth and yield 40 to 44%. Flumioxazin killed both crops when the mulch was not irrigated; and reduced squash yield 56% when irrigated. With irrigation, flumioxazin did not impact tomato fruit number, but did reduce tomato weight by 25%. These studies demonstrate the safety of carfentrazone, applied on mulch prior to transplanting either squash or tomato, regardless of irrigation, and also demonstrate the safety of glyphosate and paraquat if irrigated prior to transplanting. Conversely, flumioxazin should not be applied over mulch before transplanting either crop, regardless of irrigation. Halosulfuron application over mulch should be avoided before transplanting squash, regardless of irrigation, but can be applied prior to transplanting tomato if irrigated.
Nomenclature: Carfentrazone; flumioxazin; glyphosate; halosulfuron; paraquat; squash, *Cucurbita pepo* L. 'Enterprise'; tomato, *Lycopersicon esculentum* Mill 'Amelia'.
Key words: Crop injury, crop tolerance, herbicide removal from plastic mulch, methyl bromide alternatives.

Vegetable producers have been reliant on methyl bromide (MB) for crop production in plasticulture for many years. Greater than 20 million kg of MB have been used since 1991 in over 100 crops (Gilreath et al. 2004; Ragsdale and Wheeler 1995; Webster et al. 2001). Although producers have been successful in managing pests with MB, use of MB has been severely restricted, leaving producers in desperate need for effective alternatives, especially for weed management (Culpepper et al. 2006; Gilreath et al. 2004; Webster et al. 2001).

The Montreal Protocol of 1991 defined MB as a chemical that contributes to the depletion of the Earth's ozone layer (USDA 1999). Therefore, the manufacture and importation of MB to developed countries followed a scheduled reduction plan. In 1999, a 25% reduction (1991 MB production basis) was implemented, with additional reductions in 2001 (25%) and 2003 (20%). A complete phase out of MB had been expected on December 31, 2004. However, the Georgia Fruit and Vegetable Growers Association in cooperation with The University of Georgia successfully petitioned the Environmental Protection Agency (EPA), who in turn petitioned the MB Technical Options Committee (MBTOC) of the United Nations for critical use exemptions, allowing a limited amount of MB to be available for Georgia vegetable growers through at least 2009. Regardless of the success of these critical use exemptions, elimination of MB as a soil fumigant appears imminent due to decreasing supply and increasing price.

Many vegetables are produced in Georgia using a plasticulture system, which generally consists of raised beds of soil covered with LDPE plastic mulch. Georgia vegetables produced on mulch account for an annual farm gate value of over $340 million (McKissick 2006). Currently, there is no single alternative technology that can readily substitute for MB for weed control while maintaining cost effectiveness and availability (Culpepper et al. 2006; Gilreath et al. 2004; MacRae and Culpepper 2006; Webster et al. 2001). Replacing MB requires an entire systems change, especially in controlling weeds.

One area of change by the vegetable production industry is increased dependency and use of herbicides for weed management. Georgia growers often utilize the same LDPE plastic mulch for two to four crop production cycles. Weeds, especially nutsedges (*Cyperus* spp.), emerge directly through the mulch or through old cropping holes and are present prior to crop planting. The relationship between most herbicides, mulch, and vegetable tolerance has not been extensively investigated. Herbicide registrations for vegetables, with their extremely high value, are not dependent on the level of weed control provided by the herbicide as much as the lack of herbicide injury to the crop. Three commonly used herbicides, glyphosate, paraquat, and naptalam (Anonymous 2008b,c,d), have registrations that allow their use as over-the-top applications to mulch prior to vegetable transplanting, as they will not damage the crop. Naptalam can be applied over-

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the-top of mulch in cucumber (*Cucumis sativus* L.), watermelon [*Citrullus lantus* (Thunb.) Matsum. & Nakai] and cantaloupe (*Cucumis melo* L.). Glyphosate and paraquat can be applied over-the-top of mulch prior to transplanting most vegetables as long as the herbicide is removed from the mulch with at least 1.25 cm of irrigation or rainfall in a single event prior to crop transplanting. Glyphosate and paraquat are effective in managing many weeds in mulched systems. However, they inadequately control several weeds that infest Georgia crops produced in plasticulture systems including yellow nutsedge (*Cyperus esculentus* L.), purple nutsedge (*C. rotundus* L.), *Ipomoea* morningglory, smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.], and purslane species (*Portulaca* spp.) (Anonymous 2008c,d; Chachalis et al. 2001; Culpepper et al. 2004; Webster 2006). Neither glyphosate nor paraquat provides soil residual weed control activity.

Vegetable production would benefit from the registration of additional herbicides as long as they do not negatively impact crop development. Herbicides mixed with glyphosate or paraquat applied over-the-top of LDPE plastic mulch could improve weed control. Carfentrazone, flumioxazin, or halosulfuron may be beneficial in managing the aforementioned problematic weeds (Ackley et al. 1996; Barber et al. 2003; Carey 2004; McCloskey 2003; Mize et al. 2002; Wilson and Culpepper 2003). However, herbicides can remain on mulch, which may injure crops that are transplanted soon afterwards (Gilreath and Duranceau 1986; MacRae and Culpepper 2007). Although much literature is available on weeds controlled by herbicides included in this experiment, it is critical to understand the tolerance of vegetables planted into mulched areas previously treated with these herbicides. Thus, studies were conducted in a weed-free environment to evaluate the relationship between carfentrazone, halosulfuron, flumioxazin, glyphosate, and paraquat applied over-the-top of mulch, and subsequently irrigated or not prior to transplanting summer squash or tomato.

Materials and Methods

The experiment was conducted in 2003, 2004, and 2005 with summer squash and in 2004 and 2005 with tomato near TyTy, GA. Trials were conducted in different fields each year, but all soils were Tifton loamy sands (thermic Plinthic Kandiudults) with pH ranging from 5.9 to 6.5 and organic matter ranging from 0.7 to 1.1%; typical soil for the vegetable producing areas of Georgia. Land was prepared by using a tandem disking followed by a moldboard plow. A field cultivator with double rolling baskets and S-tine harrows finalized field preparation. A 15-cm-tall and 81-cm-wide bed was prepared using a super bedder plastic layer, injecting a mixture of MB and chloropicrin (67 : 33) at 262 kg ai/ha 20 cm below the bed top, followed in the same operation with the application of a 0.032-mm (1.25-mil) LDPE plastic mulch.[1] MB application and mulch installation were implemented 2 wk prior to trial initiation following standard grower practices. MB was included in the study to eliminate all pests, thereby allowing the experiment to focus specifically on crop tolerance to herbicides applied over the mulch.

The experimental design was a randomized complete block with a factorial arrangement of six herbicide treatments and two irrigation options. Treatments were carfentrazone[2] (0.026 kg ai/ha), flumioxazin[3] (0.105 kg ai/ha), halosulfuron[4] (0.053 kg ai/ha), paraquat[5] (0.701 kg ai/ha), glyphosate[6] (0.84 kg ae/ha), and a nontreated control. Irrigation options were either irrigation prior to transplanting crops or no irrigation. A lateral pivot was used for irrigation, applying a total of 1.0 cm of water in a single event. Herbicides were applied with a CO_2 pressurized backpack sprayer equipped with flat-fan nozzles delivering 140 L/ha at 165 kPa and 4.8 km/h. A nonionic surfactant[7] at 0.25% (v/v) was included with halosulfuron and paraquat, while a crop oil concentrate[8] at 1% (v/v) was included with carfentrazone and flumioxazin. Herbicide treatments were allowed to completely dry for 4 h before the irrigation. The nonirrigated treatments were applied to the LDPE plastic mulch 2 h (when the mulch was dry) after the other treatments had received irrigation. The following day a single row of holes spaced 38 cm apart were punched through the mulch; each hole was 5 cm deep into the soil. Tomato ('Amelia') or yellow summer squash ('Enterprise') were transplanted into respective experiments. Plot size was 81 cm wide by 10 m in length, with bed spacing of 182-cm centers. One d after transplanting, all plots received 1.0 cm of irrigation to simulate a rainfall event that might cause herbicide movement from the mulch onto the tomato or squash or into the transplant hole.

Visual estimates of crop injury were taken 3 WAT using a scale of 0 (no crop injury) to 100 (crop death). Tomato plant heights and squash plant diameters on 10 consecutive plants per plot were also measured 3 WAT. At harvest, U.S. No. 1 and U.S. No. 2 marketable squash fruit (USDA 2007a) were recorded three times a week for 4 wk, totaling twelve harvests. For tomato, a single harvest was implemented and fruit was processed and sized into four categories including extra-large, large, medium, and small (USDA 2007b). A onetime harvest allowed an exact comparison of fruit size and fruit number.

Tomato and squash injury evaluations were subjected to arcsine square-root transformations. Interpretations were not different from non-transformed data; therefore, non-transformed data are presented. The assigned no-herbicide control injury evaluations of 0% were excluded from analysis to stabilize variance. Data for tomato height, squash diameter, and marketable fruit yields were subjected to ANOVA using the general linear models procedure (SAS 2003), and sums of squares were partitioned to evaluate effects of location, herbicide treatments, and irrigation (McIntosh 1983). Means were partitioned appropriately for the factorial treatment arrangement. Data were combined over locations within each crop. Interaction means were significant and separated using the appropriate Fisher's Protected LSD test at $P \leq 0.05$.

Results and Discussion

Squash Injury and Plant Diameter. In treatments that did not include irrigation prior to transplanting, severe injury ($\geq$ 25%) occurred with all herbicides except carfentrazone, which only injured squash 3%, with minor leaf speckling at 3 WAT (Table 1). Within treatments that included irrigation

Table 1. Yellow squash injury and plant diameter as affected by herbicides applied over-the-top of low density polyethylene plastic mulch and subsequent irrigation prior to transplanting.[a]

Herbicide[b]	Rate	Injury		Plant diameter	
		Nonirrigated	Irrigated[c]	Nonirrigated	Irrigated[c]
	Kg/ha	%		cm	
none		0	0	38 a	39 a
carfentrazone	0.026	3 a	4 a	39 a	37 a
flumioxazin	0.105	100 e	62* c	0 d	19* b
halosulfuron	0.053	75 d	43* b	11 c	21* b
paraquat	0.701	55 c	2* a	25 b	41* a
glyphosate	0.840	25 b	0* a	31 b	40* a

[a] Injury evaluations and diameter measurements taken 3 wk after transplanting. For injury, all ratings were compared to the nontreated control, but assigned nontreated control ratings of 0 were removed prior to analysis. Data combined over one location in 2003, 2004, and 2005. Treatment means within the same column followed by the same letter are equivalent, and * indicates that within a common herbicide, the response was significantly influenced by irrigation according to the appropriate Fisher's Protected LSD test at $P \leq 0.05$.

[b] A nonionic surfactant[7] at 0.25% (v/v) was included with halosulfuron and paraquat, while a crop oil concentrate[8] at 1% (v/v) was included with carfentrazone and flumioxazin.

[c] Irrigation (1.0 cm) was applied over plastic mulch prior to transplanting.

prior to transplanting, injury was minimal ($\leq$ 2%) with glyphosate and paraquat, as indicated by their registrations (Anonymous 2008c,d), and with carfentrazone. Regardless of irrigation, injury from both halosulfuron and flumioxazin was severe. However, this injury was reduced by at least 32% if irrigated prior to planting.

Squash plant diameters were not impacted by irrigation in the nontreated control, with diameters ranging from 38 to 39 cm (Table 1). Similar to injury data, carfentrazone did not impact plant diameter regardless of irrigation. Paraquat and glyphosate also did not impact plant diameter when the LDPE plastic mulch was irrigated prior to transplanting. Flumioxazin completely eliminated plant stand in the absence of irrigation prior to transplanting, and even reduced plant diameter 51% (to 19 cm) when the mulch was irrigated. In contrast to flumioxazin, halosulfuron did not impact plant stand (data not shown) but stunted growth 71% (to 11 cm) when not irrigated prior to transplant. When irrigated after applying halosulfuron but before transplanting, squash stunting was still severe at 46% (to 21 cm). This supports previous research that concluded that yellow squash is sensitive to halosulfuron (Webster et al. 2003).

Tomato Injury and Plant Diameter. Similar to squash, carfentrazone was the only herbicide that did not impact tomato regardless of irrigation (Table 2). Flumioxazin severely damaged or killed all tomato plants, while paraquat and glyphosate visually reduced tomato growth 28 to 30% in the absence of irrigation prior to transplanting. The persistence of paraquat on LDPE plastic mulch was observed by Gilreath and Duranceau (1986) to cause tomato injury. In a bioassay study using tomato, glyphosate did not dissipate from mulch in the absence of moisture (Gilreath and Santos 2004). In the current study, when mulch was irrigated prior to transplanting, no injury from glyphosate or paraquat was noted, but 23% stunting occurred with flumioxazin. Tomato injury by halosulfuron was unexpected, as halosulfuron has a tomato registration. Halosufluron can be applied preplant under mulches or postemergence over-the-top of tomato and mulch 2 WAT (Anonymous 2008e). Halosufluron, when

Table 2. Tomato injury and plant height as affected by herbicides applied over-the-top of low density polyethylene plastic mulch and subsequent irrigation prior to transplanting.[a]

Herbicide[b]	Rate	Injury		Plant height	
		Nonirrigated	Irrigated[c]	Nonirrigated	Irrigated[c]
	Kg/ha	%		cm	
none		0	0	49 a	47 a
carfentrazone	0.026	5 a	6 a	46 ab	47 a
flumioxazin	0.105	81 c	23* b	9 c	39* b
halosulfuron	0.053	19 ab	5 a	41 bc	47 a
paraquat	0.701	30 b	0* a	37 c	49* a
glyphosate	0.840	28 b	0* a	37 c	49* a

[a] Injury evaluations and height measurements taken 3 wk after transplanting. For injury, all ratings were compared to the nontreated control, but assigned nontreated control ratings of 0 were removed prior to analysis. Data combined over one location in 2004 and 2005. Treatment means within the same column followed by the same letter are equivalent, and * indicates that within a common herbicide, the response was significantly influenced by irrigation according to the appropriate Fisher's Protected LSD test at $P \leq 0.05$.

[b] A nonionic surfactant[7] at 0.25% (v/v) was included with halosulfuron and paraquat, while a crop oil concentrate[8] at 1% (v/v) was included with carfentrazone and flumioxazin.

[c] Irrigation (1.0 cm) was applied over plastic mulch prior to transplanting.

Table 3. Yellow squash harvest as affected by herbicides applied over-the-top of low density polyethylene plastic mulch and subsequent irrigation prior to transplanting.[a]

Herbicide[b]	Rate	Fruit number		Fruit biomass	
		Nonirrigated	Irrigated[c]	Nonirrigated	Irrigated[c]
	Kg/ha	#/ha (thousands)		kg/ha (thousands)	
none		313 a	311 a	74.0 a	74.8 a
carfentrazone	0.026	306 a	321 a	74.0 a	74.8 a
flumioxazin	0.105	0 e	136* c	0 e	32.5* c
halosulfuron	0.053	84 d	188* b	21.9 d	43.1* b
paraquat	0.701	202 c	321* a	46.3 c	72.4* a
glyphosate	0.840	261 b	316* a	58.5 b	75.0* a

[a] Data combined over one location in 2003, 2004, and 2005. Harvest occurred three times per wk for four consecutive wk. Treatment means within the same column followed by the same letter are equivalent, and * indicates that within a common herbicide, the response was significantly influenced by irrigation according to the appropriate Fisher's Protected LSD test at $P \leq 0.05$.

[b] A nonionic surfactant[7] at 0.25% (v/v) was included with halosulfuron and paraquat, while a crop oil concentrate[8] at 1% (v/v) was included with carfentrazone and flumioxazin.

[c] Irrigation (1.0 cm) was applied over plastic mulch prior to transplanting.

applied following directions on the registration, does not injure tomato (Buker et al. 2000). However, in this study, 19% tomato stunting occurred when halosulfuron was applied over-the-top of mulch and not irrigated prior to transplanting. The tomato stunting observed was likely a response to the irrigation causing halosulfuron to be washed into the plant hole from the surrounding mulch (Grey et al. 2009), leading to a high halosulfuron concentration around the tomato transplant root ball. When the mulch was irrigated prior to transplanting (and hole punching) halosulfuron did not significantly injure tomato.

Tomato plant heights in the nontreated control were 47 to 49 cm; plant heights in the treatments followed trends noted with injury data (Table 2). When the LDPE plastic mulch was irrigated prior to transplanting, tomato heights were not reduced by carfentrazone, but were reduced 82% (to 9 cm) by flumioxazin, 16% (to 41 cm) by halosulfuron, and 24% (to 37 cm) by both paraquat and glyphosate. When mulch was irrigated prior to transplanting, flumioxazin reduced tomato height (17%, to 39 cm), the only herbicide to stunt tomato growth when irrigated, relative to the nontreated control.

Squash Yield. Across 12 harvests, squash from the nontreated control produced 311,000 to 313,000 fruit/ha, with a biomass of 74,000 to 74,800 kg/ha (Table 3). Carfentrazone did not impact squash yield regardless of irrigation. In the absence of irrigation prior to crop transplant, the number of fruit harvested and their weights were reduced 17 to 20% by glyphosate, 35 to 38% by paraquat, 73% by halosulfuron, and 100% by flumioxazin. Irrigation prior to transplanting removed sufficient paraquat and glyphosate from the LDPE plastic mulch so that yields were not impacted. For halosulfuron and flumioxazin, squash yields were suppressed when the mulch was irrigated prior to transplanting; the number and biomass of squash fruit harvested was reduced 40 to 44% by halosulfuron and 56 to 59% by flumioxazin.

Tomato Yield. Tomato produced 27,000 fruit/ha with a biomass of 15,500 kg/ha in the nontreated control (Table 4). Similar to squash, carfentrazone was the only herbicide that did not impact either fruit size or total yield regardless of irrigation. When not irrigating prior to transplanting, halosulfuron, paraquat, and glyphosate had no impact on the production of either small or medium fruit, but did reduce the number of extra-large and large fruit produced (data not shown). This was likely due to a delay in crop maturity from early season stunting (Table 2). Since 60 to

Table 4. Tomato harvest as affected by herbicides applied over-the-top of low density polyethylene plastic mulch and subsequent irrigation prior to transplanting.[a]

Herbicide[b]	Rate	Fruit number		Fruit biomass	
		Nonirrigated	Irrigated[c]	Nonirrigated	Irrigated[c]
	Kg/ha	#/ha (thousands)		kg/ha (thousands)	
none		27 a	27 ab	15.5 a	15.5 a
carfentrazone	0.026	27 a	32 a	13.0 ab	15.5 a
flumioxazin	0.105	0 c	25* b	0 d	11.5* b
halosulfuron	0.053	17 b	27* ab	6.5 c	13.0* ab
paraquat	0.701	18 b	32* a	8.1 c	15.5* a
glyphosate	0.840	17 b	32* a	6.5 c	13.0* ab

[a] Data combined over one location in 2004 and 2005. Tomato was harvested once by harvesting all fruit on the vine and grading those fruit into four categories (extra-large, large, medium, small). Treatment means within the same column followed by the same letter are equivalent, and * indicates that within a common herbicide, the response was significantly influenced by irrigation according to the appropriate Fisher's Protected LSD test at $P \leq 0.05$.

[b] A nonionic surfactant[7] at 0.25% (v/v) was included with halosulfuron and paraquat, while a crop oil concentrate[8] at 1% (v/v) was included with carfentrazone and flumioxazin.

[c] Irrigation (1.0 cm) was applied over plastic mulch prior to transplanting.

70% of the tomatoes harvested were extra-large or large fruit, these losses translated into a total fruit number loss of 33 to 37%, and total fruit weight losses of at least 47% (Table 4). Irrigating prior to transplanting led to less impact on yield from flumioxazin, halosulfuron, paraquat, and glyphosate. When compared to the nontreated control, flumioxazin was the only herbicide that negatively impacted yield, causing a 25% reduction of tomato fruit biomass.

The need to include herbicides in vegetable plasticulture production systems has increased as MB production has been reduced. Herbicides that can be applied over-the-top of LDPE plastic mulch prior to planting a crop without damaging the crop will be crucial for a weed management system. Our research supports the application of glyphosate and paraquat over-the-top of mulch, with the stipulation that the mulch is washed after application with a single irrigation or rainfall of 1.0 cm prior to transplanting. Halosulfuron should not be applied over-the-top of mulch prior to transplanting squash and should only be applied preplant in tomato if a rainfall or irrigation occurs after treatment but before transplanting. Flumioxazin should not be applied over-the-top of mulch prior to transplanting squash or tomato, while carfentrazone could be applied over-the-top of mulch prior to transplanting squash or tomato without injury. Grey et al. (2009) determined that carfentrazone was sorbed by the mulch and could not be dislodged by irrigation, supporting the observations in the current study. These results have provided the necessary data to support a new Section 2(ee) registration label for carfentrazone for Georgia growers (Anonymous 2008a). This registration label allows the combination of glyphosate plus carfentrazone to be applied over-the-top of mulch to control emerged weeds and the previous crop prior to planting fruiting vegetable and cucurbit crops. This mixture has become the most common herbicidal management tool used between crops in mulched vegetable production systems in Georgia.

Sources of Materials

[1] Low density polyethylene mulch, Pliant Corp., 1475 Woodfield Road, Suite 700, Schaumburg, IL 60173.

[2] Aim™, carfentrazone-methyl. EPA Reg. No 279-3241. FMC Corp., Agriculture Products Group, 1735 Market St., Philadelphia, PA 19103. 17 p.

[3] Valor™, flumioxazin. EPA Reg. No. 59639-99. Valent USA Corp. 1333 N. California Blvd. Suite 600, Walnut Creek, CA 94596. 19 p.

[4] Sandea™, halosulfuron-methyl. EPA. Reg. No. 10163-254. Gowan Co., P.O. Box 5569, Yuma, AZ 85366-5569. 21 p.

[5] Gramoxone Inteon™, paraquat. EPA Reg. No. 100-11217. Syngenta Crop Protection, Inc., Ag Products, P.O. Box 18300, Greensboro, NC 27419. 35 p.

[6] Roundup Weathermax™, glyphosate. EPA Reg. No. 524-537. Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167. 23 p.

[7] Induce, nonionic low foam wetter/spreader adjuvant, Helena Chemical Co., Collierville, TN 38017.

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